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Intelligent transport management by integrated dynamic traffic simulation and impact assessment

Abstract:
For transport management beyond user optimal solutions, information has to be generated on efficient measures to avoid traffic disturbances which take into account environmental restrictions. This means, it is necessary to develop strategies how to obtain an optimal system state under environmental and equity objectives and balance this against individual priorities. The information on optimal traffic management strategies should then be supplied in such a way that 'transport supervisors' are able to respond quickly and flexible to changes in the traffic situation. The goal of our research is to design an intelligent decision support system that accomplishes this task. For this purpose, we combine dynamic microscopic traffic simulation tools with an assessment model in order to evaluate environmental as well as economic impacts of new management strategies and to generate optimal solution for a desired state of transport system and environment. Within the next decade, ITS will offer the technical solutions to actually apply these strategies by providing precise information on the current state of traffic (e.g. by using Floating Car Data) and by providing means for flexible traffic management such as centralised route guidance systems (RGS) (in-vehicle, dynamic traffic guidance) or electronic tolling systems.

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Key words: microscopic traffic simulation; traffic management; impact assessment; intelligent support system

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Topic Area E1
Paper No. 5114

Intelligent transport management by integrated dynamic traffic simulation and impact assessment

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1 INTRODUCTION

A challenging task of transport management and planning is to develop solutions for an efficient and environmentally friendly transport system. In congested urban areas, where financial and space restrictions prohibit extensive infrastructure extensions, this task calls for new traffic management strategies that take into account the dynamic properties of traffic: if traffic is to be redirected in space and time, not only the fact that congestion occurs but when and where is relevant. Therefore, a great hope lies in the application of intelligent transport systems (ITS) which, on the one hand, provide users with information on the current state of the transport system, and, on the other hand, offer technical solutions for managing transport networks in order to achieve strategic objectives.

However, traffic system authorities face the situation of potentially conflicting goals that have to be weighted against each other such as

- improving the movement of people and goods as well as reducing urban traffic congestion,
- achieving environmental objectives (air quality, safety, noise etc.) as well as
- social and economic goals (accessibility, economic viability, equitable transport system).

Furthermore, if each traveller is provided with information on his or her optimal choice of transport mode or route independently, situations might occur where the choice of alternative routes may lead to unwanted effects, for example if traffic is redirected through areas with a high sensitivity against environmental impacts such as noise disturbances.

Therefore, for transport management beyond 'user optimal' solutions, information has to be generated on efficient measures to avoid traffic disturbances which take into account environmental restrictions. This means, it is necessary to develop strategies how to obtain an optimal system state under environmental and equity objectives and balance this against individual priorities. The information on optimal traffic management strategies should the be supplied in such a way that 'transport supervisors' are able to respond quickly and flexible to changes in the traffic situation. The goal of our research is to design an intelligent decision support system that accomplishes this task. Within the next decade, ITS will offer the technical solutions to actually apply these strategies by providing precise information on the current state of traffic (e.g by using Floating Car Data) and by providing means for flexible traffic management such as centralised route guidance systems (RGS) (in-vehicle, dynamic traffic guidance) or electronic tolling systems.

For the time being, as long as such technologies are not available, transport planning and management strategies to avoid negative environmental impacts, for example the restriction of roads for certain types of transport at certain periods of the day, can be designed based on typical traffic situations. First of all, it is therefore necessary to identify such traffic and corresponding environmental impact patterns for urban transport and assess the reaction of travellers to specific measures. This requires to develop dynamic integrated traffic simulation and impact assessment tools. In this paper we briefly present first results of this development in order to estimate to which extend reductions of environmental impacts could at best be achieved by new management strategies. Based on these results we develop concrete reduction scenarios from which we will learn further for the future application of intelligent management systems.

2 INTEGRATION OF MODELS

In the first step, traffic simulation tools have been linked with environmental and economic assessment tools. For this purpose, dynamic microscopic traffic simulation tools have been chosen that model a large number of individual driver-vehicle units and their mutual interactions faster than real-time. These tools are the basis for providing transport users with information on their optimal choice of transport mode or route.

2.1 Dynamic Microscopic Transport Model

In our project, we apply a dynamic microscopic transport model for the study area of Cologne that describes the interaction of cars with each other and with traffic management systems by means of a simplistic approach (Gawron, 1999, Krauß, 1998). In order to simulate the roughly three million trips happening in Cologne each day, a really fast simulation is needed. This is achieved by using a representation, where each link of the road-net is modelled as a waiting queue: cars that enter the queue (the link) have to stay there for at least the minimum travel time. After this time, they can reach the next link in their route-plan only if there is enough space there, and if the capacity of the link they are occupying allows this (capacity means the maximum flow out of the link). Since the cars are being touched by the simulation program only a few times during their stay on the link, this method is capable of simulating Cologne in some 30 minutes CPU-time. However, in order to use a valid description of the traffic flow pattern in the city, the model has to be run a number of times in order to get an approximation to the dynamic user equilibrium. This has been done by emulating the try-and-error-process, that assumed users utilize in order to find their best route through an unknown road-net (Gawron, 1999).

The driving dynamics of the model generates sufficiently realistic driving patterns that can be used for the computation of emissions and other impacts of traffic (Eissfeldt, Schrader, 2001). Since the model can simulate a few million cars in real-time, it is capable of predicting the traffic some time in the future by simply computing faster than reality, provided the input data (origin-destination matrices (ODM) or the trip tables) are correct. The model is currently being used in a large German project named “stadtinfokoeln” for a similar purpose (Stadtinfokoeln, 2000). There, a standard demand computation has been used, however in order to have a time-dependent ODM the demand has been computed for every hour of the day (von der Ruhren *et al.*, 2001). This demand computation needs as input the socio-demographic population data and some infrastructure data such as the locations of the working–places, or in general, the occasions for a variety of different activities. Additionally, the road-net and the public transport schedule and –net have been used in order to separate the individual traffic from the remaining transportation means.

2.2 Assessment Models

Thus, the traffic simulation provides detailed data on the dynamic properties of traffic flow on all links of a given transport network. These data are used in the assessment model in order to determine emissions of gaseous substances, energy consumption, noise emissions, noise exposure, and traffic accidents as well as economic impacts. A development of new models is not required for the start, instead existing models have been implemented that have been developed for the assessment of transport infrastructure plans.

2.2.1 Emissions of Gaseous Substances and Energy Consumption Models

The emissions of gaseous substances for single vehicles depend on the vehicle characteristics, the operation mode of the vehicle, the driving situation and the environmental conditions at a given moment. The baseline data for the determination of road vehicle emissions is generally gained by measuring the emission behaviour of a representative vehicle in a laboratory setting by simulating specific driving conditions. These sets of measurements are usually aggregated either by estimating a functional relationship (e.g. the German recommendations for economic assessment of road infrastructure investments EWS; FGSV, 1997) or by clustering the data into typical driving situations (e.g. the Workbook on Emission Factors for Germany and Switzerland; INFRAS, 1999). Figure 1 displays the differences between these two approaches.

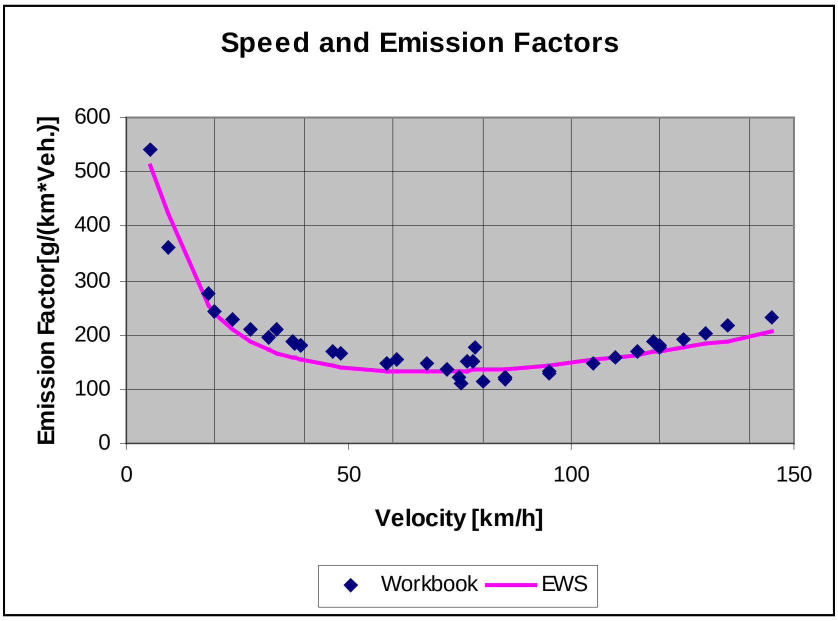

Figure 1: Speed Dependency of Emission Factors

Since in our project the dynamic reactions of travellers to management measures are of interest, it is necessary to apply an approach that is capable of reflecting changes in emissions due to changes in driving pattern. This is best fulfilled by the functional relationship approach. Therefore, in our project we applied the approach by the EWS. The basic function for the calculation of the emission factor *ef* for vehicle type *vt* and pollutant *i* depending on velocity *v* is given by

$$ef_{i,vt}(v) = \begin{cases} (c_0 + c_1 \cdot v^2 + \frac{c_2}{v}) & for \;\; v > 20 km/h \\ \min\left\{c_s, (c_0 + c_1 \cdot v^2 + \frac{c_2}{v})\right\} & for \;\; v \le 20 km/h \end{cases} \qquad [g/(km \cdot Veh.)] \qquad (1)$$

with parameters c_0, c_1 and c_2 for free flow and parameter c_s for stop-and-go traffic differentiated by vehicle type and pollutant.[1] A reduction factor is applied for each pollutant in order to take account of advanced pollution reduction technologies.

[1] These emission factors are adjusted to the road gradient by a correction factor, which is not relevant in our case study.

The calculation of road transport emissions is summarised by the following equation:

Total Emissions Road Transport: $\forall i : E_i = \sum_{vt=1}^{w} (ef_{i,vt} \cdot \sum_{k=1}^{n} (TF_{k,vt} \cdot l_k))$ (2)

where: E_i = Road Emissions of Pollutant i [kg/hour]
vt = Vehicle Type, w = Number of Vehicle Types
ef = Emission Factor [kg/Veh.km]
k = Network Section
n = Number of Sections
TV = Traffic Flow [Veh./hour]
l = Length of Section [km]

Figure 2 shows first results of the emission calculation. Emissions have been calculated for all links of the road transport in an hourly resolution. In order to derive comparable emission indicators for the town area, these emissions have been assigned to elements of a standardized grid (EMEP grid (EMEP, 1999), here 1 x 1 km^2).

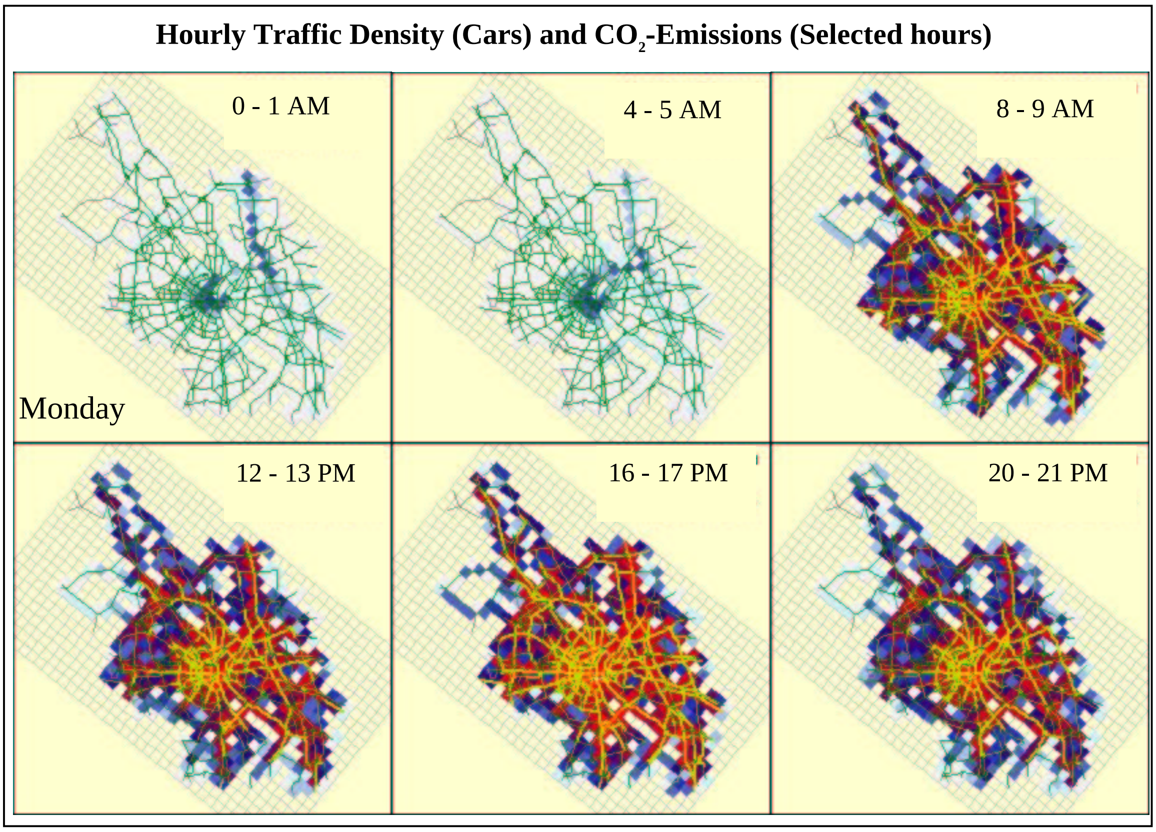

Figure 2: Hourly Traffic Density and CO_2-Emissions

For comparison reasons, we also tested a clustering approach that had been applied previously in the context of federal infrastructure planning (IWW *et al.*, 1999), where the change in annual emission quantities due to new transport projects is of interest. In this approach, emission factors are mainly clustered by road type and congestion classes, depending on traffic flow and gradient. However, not surprisingly, this highly aggregated data was not appropriate for our purposes, since the clustering by congestion classes implies a fixed composition of driving situations per congestion class which does not react to changes in traffic characteristics.

2.2.2 Modeling of Noise Emissions and Exposure

For the implementation of noise abatement regulation transport noise models have been developed that calculate noise levels or noise exposure at specific points in the vicinity of transport infrastructure. These models can be used as a basis for the environmental assessment. In this project, the reference noise level of road transport is calculated based on the noise protection manual for roads in Germany (RLS-90) (BMV, 1992). Input parameters for the calculation of emissions (equivalent sound pressure) are traffic flow, vehicle mix, speed limit, road coating, and gradient, the noise spread is determined by distance, height, topography, and meteorology. This model has been enhanced by the inclusion of reflections via the application of typical housing structures depending on the type of road. The latter are also applied to predict the number of inhabitants that are exposed to noise levels above a specified target. These are again assigned to the elements of the standardised grid (here in a higher resolution of 200 x 200 m^2 as displayed in Figure 3).

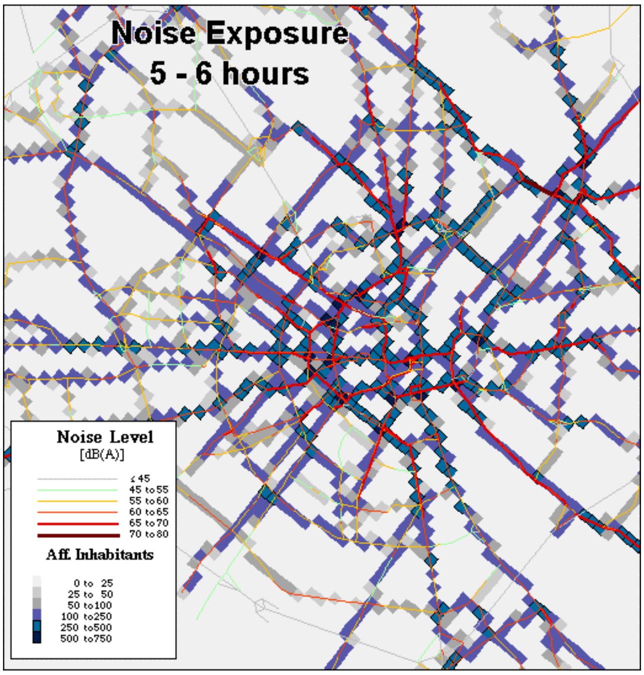

Figure 3: Noise emissions and noise exposure ≥ 55dB(A) in the early morning hour

2.2.3 Accident Models

The number of accidents on a specific road section depends on the key factors traffic density, (average and maximum) speed, and road characteristics. Traffic density and average speed are strongly interrelated. This relationship is again influenced by road characteristics. Hypothetical functions between the risk of an accident and traffic density can be derived for different road types. These curves are assumed to have a defined peak. However, such curves are not yet available for the study region. Therefore, in a first approach, average accidents rates are applied that are differentiated by road type and related to the traffic load on a section which are supplied in the guidelines for the economic appraisal of projects for Germany (EWS). A further differentiation of accident types is made in accidents with personal injuries and material damages in order to assess the significance of accidents.

2.2.4 Modeling the Economic Impacts of Strategies

Cost-benefit and multi-criteria analysis are common tools in the assessment of transport infrastructure throughout Europe. Therefore, cost values for economic impacts can be taken from standardised approaches for national infrastructure planning. In our project, we apply an approach based on the economic assessment of projects in German transport infrastructure master planning. The variable cost parts that are considered besides infrastructure and maintenance costs are vehicle operating and maintenance costs, revenues, generalised costs (time loss e.g. due to congestion) and accident costs (personal loss, health costs, and material damage).

3 DEVELOPMENT AND ASSESSMENT OF STRATEGIES

Commonly, the assessment of infrastructure projects as well as transport strategies follows the procedure of first defining a strategy or planning measure, then forecasting its effects and finally evaluating these by means of multi-criteria analysis (MCA) or cost-benefit analysis (CBA). This means that either environmental impacts have to be explicitely weighted against other impacts (MCA) or be valued in monetary terms (CBA). Both methods have major drawbacks, especially in the consideration of environmental risks, of irreversible damages, and of the interests of future generations (see Gühnemann, 2000). The result of the procedure is a statement whether a certain strategy is preferable or not. However, in our project, the strategies have to be the outcome of an optimisation process. For these reasons, the *backcasting approach* is commendable which has recently been applied in a number of projects (IWW *et al.*, 1999, OECD, 2000, UCL *et al.*, 2000). This approach is based on the definition of environmental objectives and indicators which can be used as restrictions in the optimisation process. In an iterative process, different strategies are evaluated with respect to the achievement of these targets until at least one valid solution is found. From a set of feasible strategies that strategy is finally chosen that maximises the economic welfare of society. Thus, it is possible to develop cost efficient measures that fulfil the requirements of environmental sustainability.

A major requirement is the definition of environmental targets that reflect safe minimum standards according to the rule that "destruction of irreversible natural stock should be avoided unless the social costs of conservation are unacceptably large" (Pearce et al., 1990, p. 16). Based on a literature survey (Gühnemann, 2000) the following standards are proposed for our project as a first working base:

- reduction of CO_2-emissions and fuel consumption by 30% compared to status quo,
- target levels for noise exposure: 55 dB(A) night-time, 65 dB(A) day-time,
- reduction of fatalities and severe injuries by 40% each,
- reduction of NO_x and VOC emissions by 30% each,
- reduction of emissions of particles and benzene by 90% each.

These targets will in a second step be regionally differentiated according to data on the sensitivity of the environment.

The goal of our project is to develop an intelligent support system that to some extend automatically generates typical traffic situations from real world data, simulates the effects of proposed traffic management measures in these situations, evaluates whether the safe minimum standards are achieved, and based on the economic evaluation learns best practice solutions from the optimisation process. Therefore, in a first step, such typical traffic and impact situations have been identified.

Figure 4 shows the daily fluctuation of traffic flows, environmental and economic impacts for the case study as a result of the traffic simulation and assessment models. From this, some typical situations can be identified:

- traffic flow: traffic patterns can be distinguished into night, morning peak, daytime, high afternoon peak, evening;
- CO_2-emissions: as for traffic flow with a higher peak in congested afternoon situation;
- noise exposure: strong early morning and late evening peaks due to stricter night-time (22 - 6 h) target noise levels;
- user costs: as for CO_2, but with even a stronger 'explosion' of costs in the congested afternoon situation;
- accidents: strictly proportional to traffic flow.

From this picture, we developed first example strategies for the reduction of noise exposure and CO_2-emissions in order to identify the scope of potential improvements that can be achieved by management strategies.

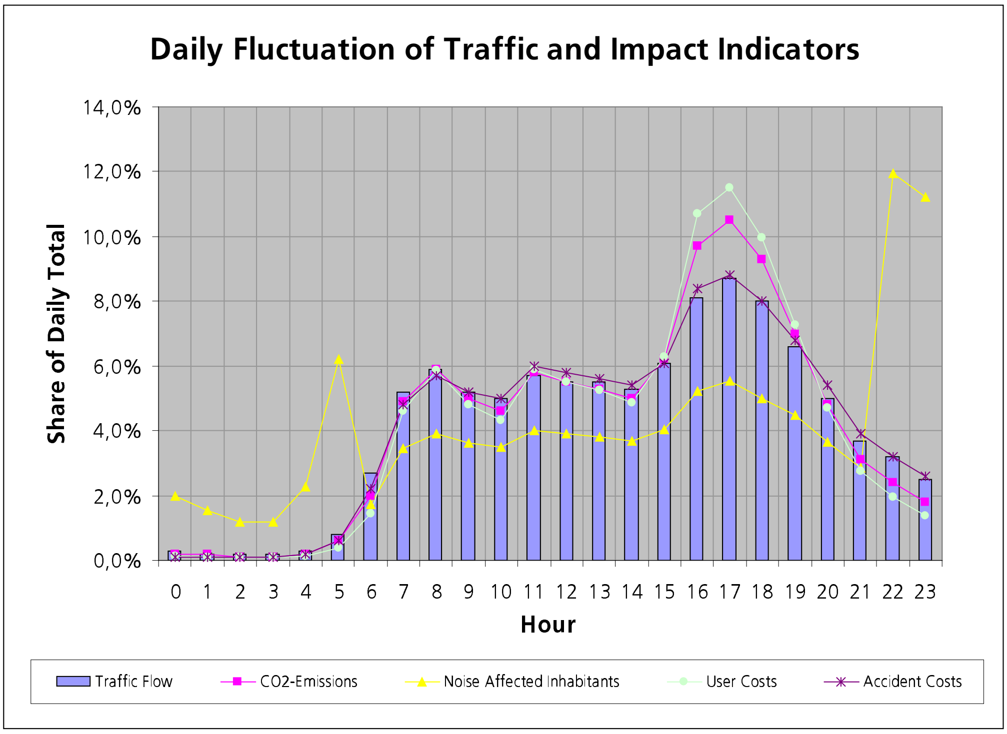

Figure 4: Daily Fluctuation of Traffic and Impact Indicators

3.1 Strategies for the Reduction of Noise Exposure

The noise situation described above has shown that it is necessary to develop reduction strategies take into account the time and place of occurrence. Parameters that influence the development of noise are traffic flow, traffic mix (share of trucks), speed, and coating; noise exposure is further influenced by the population density in affected areas and environmental variables such as meteorology and topography. In our first test, we keep all parameters but the traffic speed constant in order to evaluate what effect can be achieved by a targeted reduction of speed limits in highly affected areas and during high-exposure time. Therefore, for streets where the noise target level has been exceeded at night-time, the speed limit has been decreased by 10 km/h at night, respectively if the day-time target was exceeded, the speed limit was equally decreased during the day. Figure 5 shows the effects of this measure on noise exposure and user costs over the day. However, the effect does not yet include a modified route choice of users due to the change in travelling times.

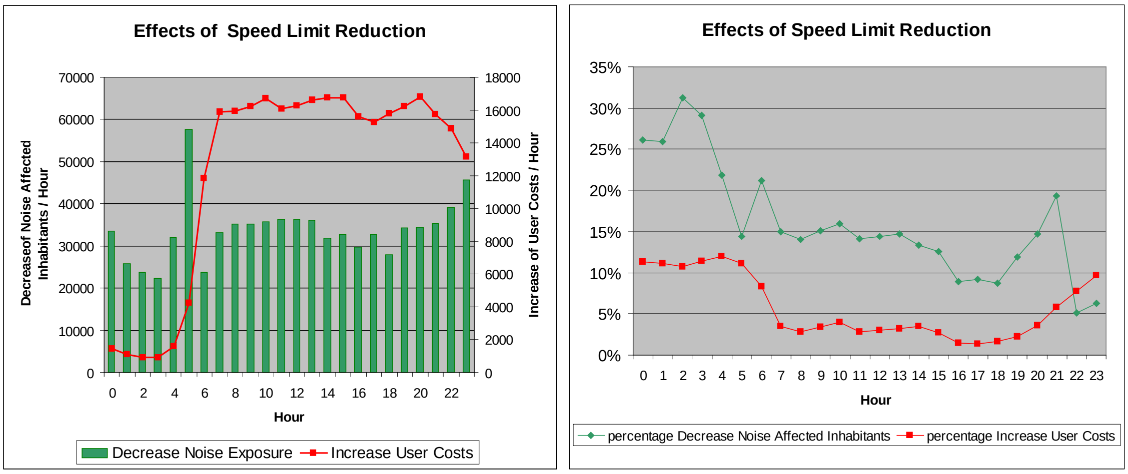

Figure 5: Effects of Speed Limit Reduction on Noise Exposure and User Costs

The highest reductions could actually be achieved during the morning peak hour. In total, the noise exposure of inhabitants, measured by the total amount of hours where inhabitants are affected by noise above the target level, could be decreased by 13% while the user costs where increased by 3%. This equals costs of about 0.3 DM per inhabitant and hour exposed. The problem of this approach is that user costs are counted and weighted with every second of time loss. As a comparison, the EWS suggests a basic cost value of 85 to DM per year and inhabitant which increases with the value of the target level exceedance. Figure 6 shows that the main improvements could be achieved in the city centre.

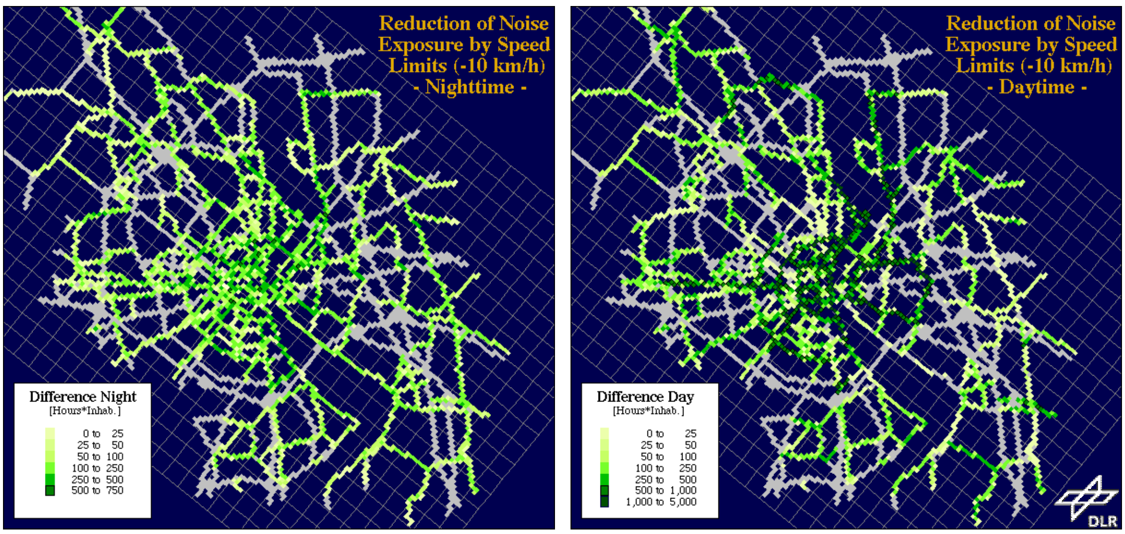

Figure 6: Local Improvements of Noise Exposure due to Speed Limit Reduction

Though a significant reduction of noise exposure could be achieved, the target levels of 55 dB(A) at night-time and 65 dB(A) at daytime are by far not achieved. Therefore, it is necessary to further strengthen the efforts for noise reduction. However, the effectiveness of this type of measure –reducing speed– is limited: According to the RLS-guidelines on noise protection, a maximum of about 9 dB(A) reduction can be achieved by reducing speed limits from 100 km/h to 20 km/h. Another drawback is that below 20 km/h (i.e. in congested traffic situations) a valid statement is not possible on the basis of the noise models that are available for the assessment of transport infrastructure projects. Other measures that will be tested in the next steps are a differentiated re-routing of travellers and technological measures that reduce noise emissions of vehicles. In future it could be possible to provide access to restricted areas at certain times based on information on vehicle's noise characteristics that is provided by intelligent transport systems. However, for the purpose of assessing such traffic management strategies it will be necessary to develop more refined noise emission and exposure models.

3.2 Strategies for the Reduction of Emissions and Fuel Consumption

As we could see in Figure 4, besides traffic flow, congestion does have a strong influence on the quantity of emissions that is produced. A third important factor is the technology that is applied to reduce emissions and fuel consumption. Hence, strategies can be thought of that improve the traffic flow in order to reduce congestion, reduce the total amount of road traffic and/or encourage the introduction of environmentally friendly technologies. In a first step, we estimate the emission reduction potential of strategies for traffic flow improvement. Figure 7 displays the average specific emission during the day for CO_2.

It shows that during congested situations the average specific emissions are about 75% higher than under free flow conditions. Let us assume that it would be possible in peak hours to manage the same traffic flow without congestion, i.e. the minimum average specific CO_2-emissions could be applied to these flows as well. Then a total reduction of CO_2-emissions of about 30% could be achieved. Since of course our first assumption does not hold true, this value only indicates the absolute maximum of emission reduction that would be possible by introducing intelligent traffic management systems.

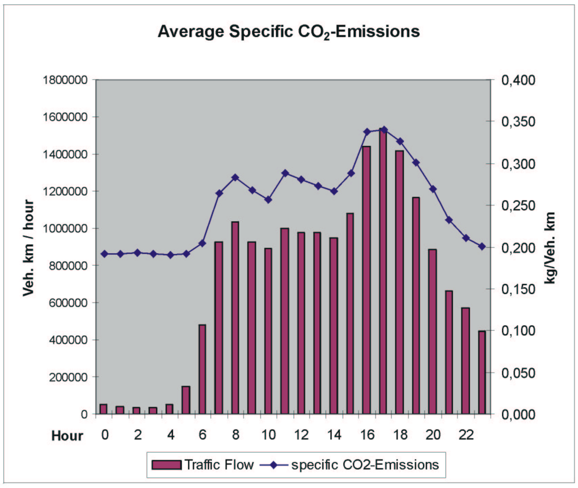

Figure 7: Average specific CO_2-emissions

Since CO_2-emissions are strictly proportional to fuel consumption, these conclusions hold true for fuel consumption as well. As can be seen in Figure 8, a different situation can be observed for NO_x-emissions. Since NO_x-emissions show a strong speed dependency, a reduction of congestion that comes along with an increase in speed does not lead to a decrease as for CO_2-emissions. On the other hand, a reduction of speed has the contrary effect: the speed limit reduction that has been assumed in the noise case leads to decrease of NO_x-emissions by 1.5% but to an increase of CO_2-emissions by 1.5%. Therefore, other measures that are directed towards achieving a steady traffic flow at an optimal speed have to be developed. Until now, the influence of traffic signals and other measures that influence driving patterns cannot not been considered in the emission models. For example, technologies could be implemented that improve the anticipation of traffic situations by drivers. This shows the importance of developing adequate emission models which are capable of reflecting dynamic changes.

Additionally, technical measures that are available to reduce emissions will be analysed. As in the case of noise, it can be imagined that specific, sensitive city areas will be priced or restricted for access depending on the emission reduction equipment or type of vehicle. For example, the use of zero emission or alternative propulsion vehicles could be encouraged by this kind of measures. The emission and fuel consumption reduction potential of technological measures is expected to be very high.

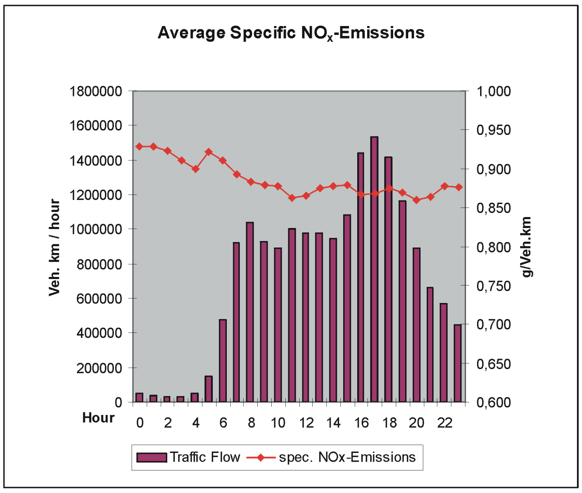

Figure 8: Average specific NO_x-emissions

For example, EWS state a reduction of fuel consumption by cars between 1990 and 2010 by about 15%, of NO_x-emissions by about 90% for gasoline, 50% for diesel cars. The technological potential for reducing fuel consumption of cars is presently analysed in an ongoing project of the DLR. However, assuming a further increase in traffic demand, this technological potential might be consumed soon. Therefore, additional transport management measures that aim at a modal shift towards less energy consuming transport modes will be analysed. This requires the development of multi-modal dynamic transport and assessment models, an integration of intelligent traffic systems and cross-modal management strategies.

4 CONCLUSIONS / OUTLOOK

With our work to date we have laid the foundations for developing strategies for a transport management beyond user optimal solutions. Fast microscopic and dynamic transport models for road traffic are available that simulate the reactions of users to interventions into the transport system with high accuracy and thus can be used in traffic management systems as well as serve as a basis for the assessment of management strategies. For a comprehensive transport management in urban areas it is necessary to extend these models to other transport modes such as public and non-motorized transport. Environmental and economic impact models have been applied that have initially been developed for transport planning purposes. Though these models provide satisfactory results for a first assessment of strategies it could be seen that there is still substantial research demand for developing models that are capable of mapping impacts at a dynamic and microscopic scale which is necessary to assess the impacts of management strategies.

Nevertheless, through the application of these models some experience has been gained on potential transport management strategies in the examined study area that could be applied in order to avoid or minimize negative environmental impacts. In particular:

- For the reduction of noise emissions and exposure it is necessary to design spatially and temporally targeted strategies. General speed limits are not very effective but costly.
- There is a great potential for reducing fuel consumption and CO_2-emissions through the application of strategies that aim at improving traffic flow. Furthermore, considerable reductions can be achieved by encouraging the use of less consuming technologies.
- The reduction of NO_x-emissions requires a reduction of speed that is quite contrary to those of CO_2 emissions and fuel consumption. However, technical development will most probable solve the problem of NO_x-emissions and other compounds alone.

A major requirement for our future work is the formalisation of the problem of finding the system optimum under environmental constraints and economic efficiency in order to automatically generate optimal strategies. The implementation requires

1. operational criteria for the assessment of strategies;
2. the formulation of a general cost function in a multi-criteria decision context in order to define what the system optimum is meant to be;
3. detailed information on the reaction of transport users to measures;
4. the development of fast tools for the simulation of traffic and environmental impacts as well as for the assessment of strategies in order to find system optimal solutions depending on the current state of the transport system.

From the results of our research project it will then be possible to assess whether the application of intelligent transport management systems will be feasible in future traffic guidance centers and will support traffic supervisors in their decision on best traffic management strategies.

ACKNOWLEDGEMENTS

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